Claims

1. An adaptive control system (ACS) generating at least one control signal δ_c to regulate a plant output signal y by feedback of the plant output signal y, and optionally other sensed variables affecting the state of the plant, the plant output signal y being a function of the full plant state having known but unrestricted relative degree r.

2. An ACS as claimed in claim 1 wherein the ACS controls the plant output signal y based on an approximate linear dynamic model, and controls unmodeled plant dynamics using adaptive control.

3. An ACS as claimed in claim 2 wherein the ACS comprises an adaptive element to implement adaptive control of the plant output signal y, the adaptive element comprising a neural network.

4. An ACS as claimed in claim 3 wherein the adaptive element uses at least one time-delayed version y_d of the plant output signal y, that is supplied together with the plant output signal y as inputs to the neural network, the neural network generating an adaptive control signal ν_{ad} contributing to generation of the control signal δ_c to control the plant output y inspite of unmodeled plant dynamics, based on the time-delayed signal y_d and the plant output signal y, the time-delayed version signal y_d and the plant output signal y ensuring boundedness of the tracking error $\tilde{y}$.

5. An ACS as claimed in claim 3 wherein the neural network of the adaptive element comprises at least one basis function ϕ and at least one connection weight W used to generate an adaptive control signal ν_{ad} contributing to generation of the command control signal δ_c, the adaptive element further comprising an error conditioning element coupled to receive the basis function ϕ, the error conditioning element filtering the basis function ϕ with a transfer function $T^{-1}(s)$ to produce

filtered basis function ϕ_f used to modify the connection weight(s) W of the neural network through feedback to ensure boundedness of the tracking error $\tilde{y}$.

6. An ACS as claimed in claim 1 wherein the ACS comprises a command filter unit generating an rth derivative $y_c^{(r)}$ of the plant output signal y in which r is an integer indicating the number of times the plant output signal y must be differentiated with respect to time before an explicit dependence on the control variable is revealed.

7. An ACS as claimed in claim 1 wherein the ACS comprises:

an error signal generator generating a tracking error signal $\tilde{y}$ indicating the difference between the plant output signal y and a commanded output signal y_c;

a linear controller coupled to receive the tracking error signal $\tilde{y}$, the linear controller generating a transformed signal $\tilde{y}_{ad}$ based on the tracking error signal $\tilde{y}$; and

an adaptive element coupled to receive the transformed signal $\tilde{y}_{ad}$ and generating an adaptive control signal ν_{ad} based thereon, the adaptive element operating on the transformed signal $\tilde{y}_{ad}$ to generate the adaptive signal ν_{ad} such that the transfer function from ν_{ad} to $\tilde{y}_{ad}$ is strictly positive real (SPR).

8. An adaptive control system (ACS) for controlling a plant based on at least one commanded output signal y_c and an rth time-derivative of the commanded output signal $y_c^{(r)}$, and a plant output signal y that is a function of the states existing in the plant, r being the relative degree of the plant output signal y, the ACS comprising:

a model inversion unit (MIU) coupled to receive a pseudo-control signal ν and a plant output signal y, the MIU generating a control signal δ_c by inverting an approximate model of the plant dynamics, the MIU supplying the control signal δ_c to the plant for control thereof;

a summing unit coupled to receive the rth time-derivative of the commanded output signal $y_c^{(r)}$, a pseudo-control component signal ν_{dc}, and an adaptive control signal ν_{ad}, the summing unit adding the rth time-derivative of the commanded output signal $y_c^{(r)}$ and the pseudo-control component signal ν_{dc}, and subtracting the adaptive control signal ν_{ad}, to generate the pseudo-control signal ν;

an error signal generator (ESG) coupled to receive the commanded output signal y_c and optional derivatives thereof and the plant output signal y, the ESG generating a tracking error signal $\tilde{y}$ by differencing corresponding signal components of the commanded output signal y_c and optional derivatives thereof, and a plant output signal y;

a linear controller having a linear dynamic compensator (LDC) coupled to receive the tracking error signal $\tilde{y}$, the LDC generating a pseudo-control component signal ν_{dc} based on the tracking error signal $\tilde{y}$, the pseudo-control component signal ν_{dc} for stabilizing the feedback linearized dynamics of the model inverted in the model inversion unit, the LDC generating a transformed signal $\tilde{y}_{ad}$ based on the tracking error signal $\tilde{y}$ so that a transfer function from an adaptive control signal ν_{ad} to the transformed signal $\tilde{y}_{ad}$ is strictly positive real (SPR);

an adaptive element having

an error conditioning element coupled to receive the transformed signal $\tilde{y}_{ad}$ and at least one neural network basis function ϕ, the error conditioning element stable low-pass filtering the basis function ϕ to produce a

filtered basis function ϕ_f and multiplying the filtered basis function ϕ_f by the transformed signal $\tilde{y}_{ad}$ to produce a training signal δ; and

a neural network adaptive element (NNAE) coupled to receive the plant output signal y, the pseudo-control signal ν_{ad}, and the training signal δ, the NNAE having a neural network generating the adaptive control signal ν_{ad} based on the plant output signal y and the pseudo-control signal ν_{ad} supplied as inputs to the neural network, the neural network generating the adaptive control signal ν_{ad} by mapping the plant output signal y and a pseudo-control signal ν to the adaptive control signal ν_{ad} based on at least one basis function ϕ and at least one connection weight W that is an output signal from the neural network, the adaptive element using the training signal δ to update the basis function ϕ and at least one connection weight W of the neural network so that the adaptive control signal ν_{ad} generated by the neural network is bounded.

9. An ACS as claimed in claim 8 wherein the LDC maps the tracking error signal $\tilde{y}$ to the pseudo-control component signal ν_{dc} based on a transfer function $N_{dc}(s)/D_{dc}(s)$, and the LDC maps the tracking error signal $\tilde{y}$ to the transformed signal $\tilde{y}_{ad}$ based on a transfer function $N_{ad}(s) / D_{dc}(s)$, the transfer functions $N_{dc}(s)/D_{dc}(s)$ and $N_{ad}(s) / D_{dc}(s)$ selected to assure boundedness of the tracking error signal.

10. An ACS as claimed in claim 8 further comprising:

a delay element coupled to receive the plant output signal y and generating at least one delayed plant output signal y_d as an additional input signal to the neural network to generate the adaptive control signal ν_{ad}.

11. An ACS as claimed in claim 8 further comprising:

a delay element coupled to receive the pseudo-control signal ν and generating at least one delayed pseudo-control signal ν_d, the delay element coupled to

supply the delayed pseudo-control signal ν_d as an additional input signal to the neural network to generate the adaptive control signal ν_{ad}.

12. An ACS as claimed in claim 8 wherein the plant comprises at least one sensor sensing at least one state of the plant, and generating the plant output signal y based on the sensed plant state.

13. An ACS as claimed in claim 8 wherein the plant comprises at least one actuator controlling the plant based on the command control signal δ_c.

14. An ACS as claimed in claim 8 wherein the ACS is operated by a human operator, the ACS further comprising:

an operator interface unit coupled to receive the plant output signal y, the operator interface unit generating a display signal based on the plant output signal y;

the operator receiving the display signal from the operator interface unit, and producing control action to control the plant based on the display signal; and

a command filter unit operable by the operator, the command filter unit generating the commanded output signal y_c and optional derivatives thereof, and the rth derivative $y_c^{(r)}$ of the plant output signal y based on control action of the operator.

15. An ACS as claimed in claim 8 further comprising:

an operator interface unit coupled to receive the plant output signal y, the operator interface unit generating a signal based on the plant output signal y;

an operator coupled to receive the signal generated by the operator interface unit, and generating an operator signal to control the plant based on the signal generated by the operator interface unit; and

a command filter unit operable by the operator, the command filter unit generating the commanded output signal y_c and optional derivatives thereof, and the rth derivative $y_c^{(r)}$ of the plant output signal y based on the operator signal.

16. A linear controller coupled to receive a tracking error signal $\tilde{y}$ that is a vector difference of a plant output signal y that is a function of a full plant state having known but unrestricted relative degree r, and a commanded output signal y_c, the linear controller generating a pseudo-control component signal ν_{dc} based on a transfer function $N_{dc}(s)/D_{dc}(s)$ and the tracking error signal $\tilde{y}$, the pseudo-control component signal ν_{dc} used by the linear controller to control the plant based on an approximate linear model, and the linear controller generating a transformed signal $\tilde{y}_{ad}$ based on a transfer function $N_{ad}(s)$ / $D_{dc}(s)$ and the tracking error signal $\tilde{y}$, the transformed signal $\tilde{y}_{ad}$ used for adaptive control of the plant, the transfer functions $N_{dc}(s)/D_{dc}(s)$ and $N_{ad}(s)/D_{dc}(s)$ selected to assure boundedness of the tracking error signal.

17. An adaptive element (AE) of an adaptive control system (ACS) for controlling a plant based on a plant output signal y that is a function of the full plant state existing in a plant, a pseudo-control signal ν used to control the plant, and a transformed signal $\tilde{y}_{ad}$ from a linear controller of the ACS, the adaptive element comprising:

a neural network adaptive element (NNAE) comprising a neural network having at least one connection weight W and at least one basis function ϕ, the neural network coupled to receive the pseudo-control signal ν and the plant output signal y;

a delay element coupled to receive the plant output signal y and the pseudo-control signal ν, and generating signals y_d, ν_d that are delayed versions of the plant output signal y and the pseudo-control signal ν; and

an error conditioning element coupled to receive the transformed signal $\tilde{y}_{ad}$ and the basis function ϕ, and generating an error signal δ based thereon,

the NNAE coupled to receive the error signal δ and adapting the connection weight W and the basis function ϕ to adaptively control unmodeled plant dynamics.

18. An adaptive element as claimed in claim 17 wherein the error conditioning element includes a filter and a multiplier, the filter operating on the basis function ϕ from the NNAE to produce a filtered basis function ϕ_f, the multiplier generating the error signal δ by multiplying the filtered basis function ϕ_f by the transformed signal $\tilde{y}_{ad}$.

19. An adaptive element as claimed in claim 18 wherein the filter operates on the basis function ϕ to produce the filtered basis function ϕ_f using a transfer function $T^{-1}(s)$ that ensures boundedness of the connection weight W and the tracking error signal.

20. A method comprising the step of:

a) generating at least one command control signal δ_c to regulate a plant output signal y by direct feedback of the plant output signal y, and optionally other sensed variables affecting the state of the plant, y being a function of the full plant state having known but unrestricted relative degree r.

21. A method as claimed in claim 20 wherein the control signal δ_c is generated in step (a) so as to control the plant output based on an approximate linear dynamic model, and so as to control the plant output in spite of unmodeled plant dynamics based on an adaptive control technique.

22. A method as claimed in claim 20 wherein the adaptive control technique is implemented with a neural network.

23. A method comprising the steps of:

a) selecting a transfer function $N_{dc}(s)/D_{dc}(s)$ used in control of a plant based on a plant output signal y that is a function of all states existing in the plant, and a transfer function $N_{ad}(s)/D_{dc}(s)$ used in adaptive control of the plant based on the plant output signal y, to ensure boundedness of the tracking error signal.

24. A method comprising the steps of:

a) generating a tracking error signal $\tilde{y}$ that is a vector difference of a plant output signal y that is a function of all states existing in a plant, and a commanded output signal y_c;

b) generating a pseudo-control component signal ν_{dc} based on a transfer function $N_{dc}(s)/D_{dc}(s)$ and the tracking error signal $\tilde{y}$; and

c) generating a transformed signal $\tilde{y}_{ad}$ based on a transfer function $N_{ad}(s)/D_{dc}(s)$ and the tracking error signal $\tilde{y}$.

25. A method as claimed in claim 24 further comprising:

d) controlling a plant with the pseudo-control component signal ν_{dc}, the pseudo-control component signal ν_{dc} controlling the plant based on an approximate linear model; and

e) controlling the plant adaptively based on the transformed signal $\tilde{y}_{ad}$ used for adaptive control of the plant.

26. A method as claimed in claim 24 further comprising the steps of:

d) receiving a plant output signal y that is a function of all states existing in a plant;

e) delaying the plant output signal y to produce a delayed signal y_d;

f) receiving a pseudo-control signal ν used to control the plant;

g) delaying the pseudo-control signal ν to produce a delayed signal ν_d; and

h) supplying the signals y, y_d, ν, ν_d to a neural network to generate an adaptive control signal ν_{ad} to control the plant.

27. A method as claimed in claim 26 further comprising the steps of:

i) filtering at least one basis function ϕ to generate a filtered basis function ϕ_f;

j) multiplying the filtered basis function ϕ_f by the transformed signal $\tilde{y}_{ad}$ to produce an error signal δ; and

k) modifying at least one connection weight W of the neural network based on the error signal δ.

28. A method as claimed in claim 27 further comprising the steps of:

l) differentiating the plant output signal y r times to produce an rth derivative signal $y_c^{(r)}$ of the plant output signal y, r being the relative degree of the plant output signal;

m) summing the rth derivative signal, the pseudo-control component signal ν_{dc}, and the adaptive control signal ν_{ad}, to generate a pseudo-control signal ν; and

n) generating a command control signal δ_c based on the pseudo-control signal ν and the plant output signal y by model inversion.

29. A method comprising the steps of:

a) receiving a plant output signal y that is a function of all states existing in a plant;

b) delaying the plant output signal y to produce a delayed signal y_d;

c) receiving a pseudo-control signal ν used to control the plant;

d) delaying the pseudo-control signal ν to produce a delayed signal ν_d; and

e) supplying the signals y, y_d, ν, ν_d to a neural network to generate an adaptive control signal ν_{ad} to assist a linear controller in controling the plant.

30. A method as claimed in claim 29 further comprising the steps of:

f) filtering at least one basis function ϕ to generated a filtered basis function ϕ_f;

g) multiplying the filtered basis function ϕ_f by the transformed signal $\tilde{y}_{ad}$ to produce an error signal δ; and

h) modifying at least one connection weight W of the neural network based on the error signal δ.